

## **Tidal Channels of Skagit Bay: Three-Dimensional Hydrdynamics and Morphodynamic Evolution**

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### **LONG-TERM GOALS**

To measure and model the dynamics of currents, waves, and sediment transport over tidal flats, with particular emphasis on interactions between water flows and bathymetry. To improve insight and predictive capabilities through model-data comparisons.

### **OBJECTIVES**

1. To measure water flows and bathymetric evolution within and around the tidal channels of Skagit Bay.
2. To explain and model observed flow patterns.
3. To explain the observed interactions between hydrodynamics and bathymetric evolution.

### **APPROACH**

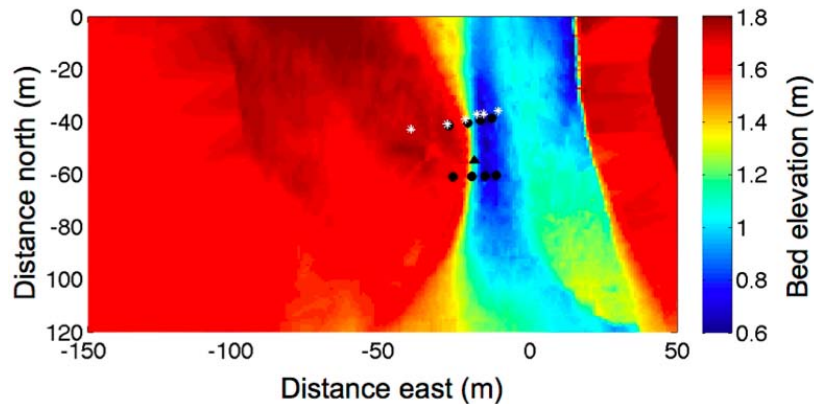
During FY2010, we have worked to analyze data collected during field experiments in FY2008-2009, and to develop and test models. During the experiments we deployed arrays of instruments, especially Acoustic Doppler Current Profilers (ADCPs), to resolve in detail the vertical and horizontal variations in flows within and near tidal channels. Multi-month deployments of fixed instruments measured the persistent flows responsible for bathymetric evolution. Repeated GPS surveys measured bathymetric evolution. Brief, intensive deployments of mobile current meters, CTDs, and drifters resolved flows in greater detail.

To simulate the density-driven flows observed near the channel-edge, we have used analytic and numerical models that have been widely applied in deeper water. To simulate the dissipation of waves within a saltmarsh neighboring the channel, we have derived novel analytic and numerical models. To understand the propagation of thin surface layers of freshwater across the flooded tidal flats, we have combined flow measurements with equations for conservation of mass, momentum, and energy. To examine interactions between hydrodynamics and bathymetric evolution, we will

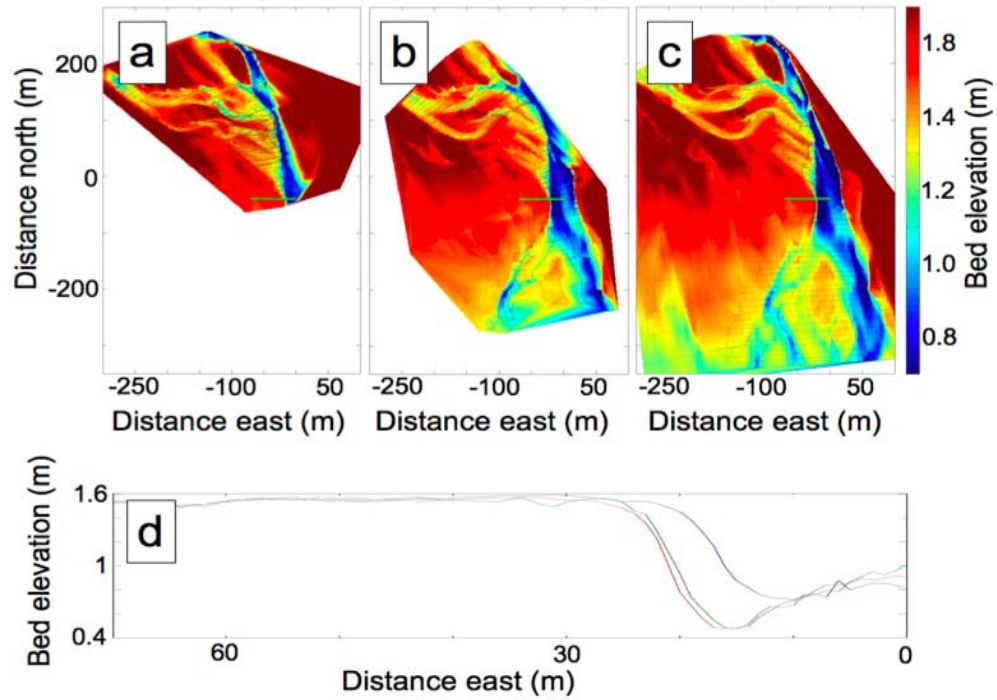
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substitute flow measurements into simple sediment transport formulas, and compare predictions with observed morphological evolution.

Key individuals include Stephen Henderson (PI), Julia Mullarney (a Postdoctoral Researcher helping to coordinate fieldwork and undertake analysis), and graduate students Kassondera Dallavis and Alyson Day (contributing to fieldwork and analysis).



***Figure One: Locations of fixed instruments during May (white stars) and June–August (ADCPs black circles, vertically-spaced CTDs black triangle). Color scale indicates bed elevation, with periodically-flooded tidal flats marked by red area, and permanently-flowing tidal channel marked by blue-green. [During May, six instruments were deployed in a single 40-m-long transect extending from tidal flats and across the curved western edge of a 40-m-wide, 1.2-m deep tidal channel which runs north-south. During June-August, two 4-instrument, 20-m-long transects crossed the channel-edge. These two transects were displaced by 20m in the along-channel direction.]***



**Figure 2: Bathymetric surveys for May (a) June (b) and July (c) 2009 (further surveys from Sept 2008, late July 2009, and August 2009 not shown). Cross-sections through surveyed channel edge bathymetry (d) for May (blue) June (green) and July (red) (location of cross-sections is indicated in (a)–(c) by green line).**

**[Repeated bathymetric surveys in a 300 m by 500 m region show a tidal channel surrounded by unmoving tidal flats. Cross-sections show that the channel edge moved about 10 m between May and June]**

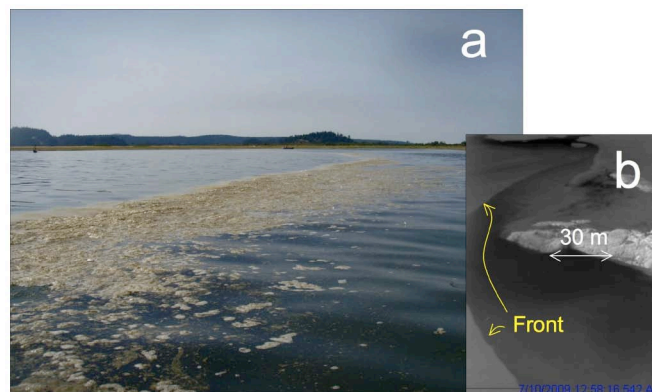
## WORK COMPLETED

During FY09, eight ADCPs, two CTDs, and 5 temperature gauges were deployed in Skagit Bay for 16 weeks. Fixed arrays of ADCPs and CTDs measured currents and stratification (figure 1). GPS surveys measured the bathymetric evolution of a tidal channel (figure 2). During brief intensive deployments, mobile ADPs and CTDs measured spatial variability of flows in greater detail than possible with fixed instruments. We developed a novel current profiling system using paired upward- and downward-looking Pulse-Coherent ADCPs cantilevered in front of a small boat to measure intense near-surface plumes that can not be resolved using traditional methods. We deployed two ADCPs in Willapa Bay to support the efforts of other Tidal Flats DRI researchers (see related projects section below).

During FY10, we posted data on the web for use by other researchers in the tidal flats DRI. We developed algorithms to remove the velocity ambiguities that would otherwise prevent application of high-resolution Pulse-Coherent ADCPs to boat-mounted profiling. Models for channel-edge front-trapping were tested, and models for wave dissipation in a saltmarsh were developed and tested. Masters student Kassondera Dallavis wrote her Masters thesis, which her committee has approved for defense. We submitted two papers presenting results from our tidal flats experiments to the (peer reviewed) Journal of Geophysical Research.

## RESULTS

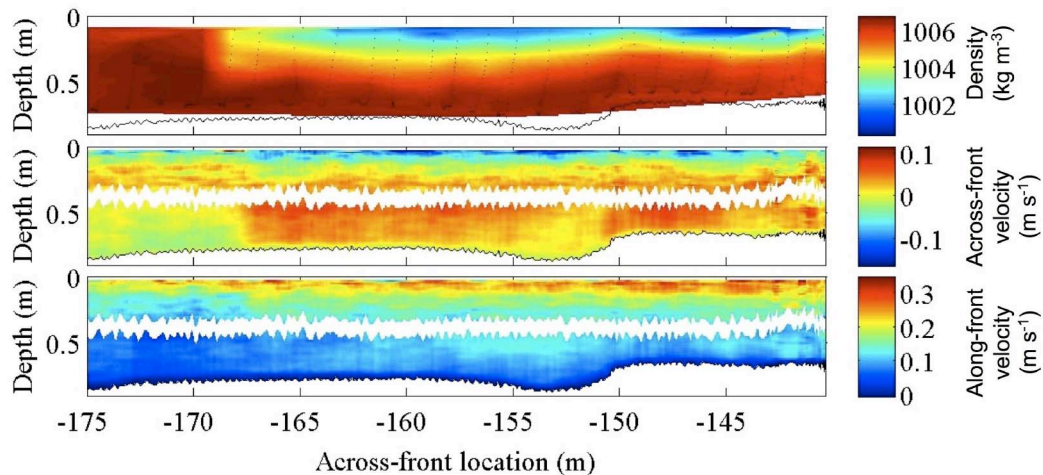
We have found that hydraulic control theory explains the formation of intense baroclinic fronts along the edges of tidal channels during the early stages of flood tide (figure 3). We showed that this mechanism may be widespread in shallow tidal-flats flows, because even weak (10m/s) flows are often supercritical during the early stages of flood tide. Mixing at these fronts was of intermediate intensity (Hogg *et al.* 2001). The strongest near-bed across-channel flows we observed were generated by these fronts, a fact potentially significant to channel bathymetric evolution. A manuscript presenting these results is under review with the Journal of Geophysical Research.



**Figure 3: Visual (left) and infrared (right) images of channel-edge surface fronts (IR image provided by Thompson and Chickadel).**

**[Fronts on the ocean surface are clearly marked by a streak of foam (visual image) and a sharp brightness contrast (IR image, marking a jump in surface temperature).]**

We found that thin (sometimes only 30-cm-thick) surface plumes of relatively fresh water can persist for hours, carrying river water kilometers across the tidal flats (figure 4). We quantified energy balances and mixing rates along the fronts bounding these plumes. One interesting result is that strong shear of the along-front velocity contributes significantly to mixing (such along-front shear is absent in laboratory and theoretical models for gravity current propagation). We observed one front halt in its propagation as it encountered an opposing, wind-generated flow. Another front propagated for 1.5 hours over the tidal flats before encountering a strongly-sheared opposing barotropic current and suddenly dissipating. We are working to test models against these observations, with the aim of improving predictions of freshwater spreading and mixing across tidal flats.



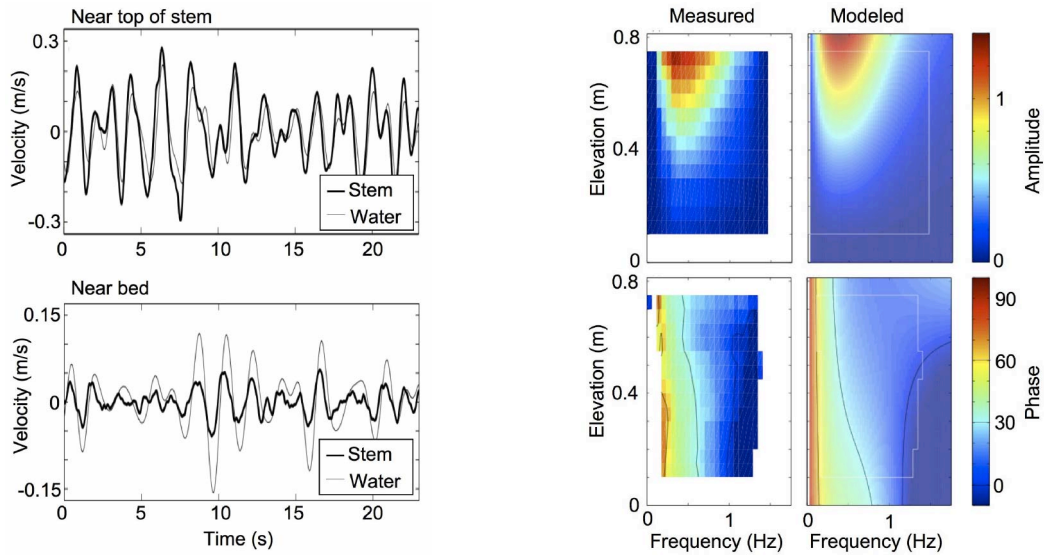
**Figure 4: Transects of density and velocity across the edge of a fresh surface plume.**  
*[Density, velocity, and depth are plotted as functions of depth and distance.  
 Fresh plume visible as low-density layer less than 0.5 m thick. Top of fresh layer is moving towards plume, underlying layer is moving away. Both along- and across-front velocities are strongly sheared at the base of the plume.]*

Even under the weak winds that prevailed during our 2009 experiment, winds were responsible for a substantial proportion of the vertical variability of observed currents. This vertical variability shows intriguing patterns: midway between the bed and the surface, shear simply increased with increasing windspeed, but near the surface shear decreased with increasing windspeed. We have found that a very simple eddy viscosity model explains the behavior at mid-depth. We will test the ability of more sophisticated models, which simulate turbulent mixing associated with breaking waves, to predict the observed near-surface shear.

We measured wave dissipation in a saltmarsh adjacent to the tidal flats, and found that most wave energy was dissipated within 10m of the marsh edge, providing still water ideal for deposition of fine sediments. We adapted the Euler-Bernoulli equations for beam bending, widely used by structural engineers, to simulate wave dissipation by flexible saltmarsh vegetation. Analytic and numerical solutions were derived, and were found to agree with vegetation motion observed using synchronized current meters and video. These results show that vegetation motion can cause



substantial and predictable reductions in wave dissipation. A manuscript presenting these results is under review with the Journal of Geophysical Research.



**Figure 5: Left: Observed motion of water and flexible stem in saltmarsh at two elevations above the bed. Right: Measured and predicted transfer function between water and stem motion (stem free end at 0.8 m).**

*[Observations near the top of a stem show stem and water move back and forth together under waves. Observations near stem base show stem motion smaller than wave motion, and leading wave motion by  $\frac{1}{4}$  of a cycle. Theoretical and observed transfer function amplitudes show that stem motions are largest relative to water motions near stem free end, and at frequencies about 0.5 Hz. Theoretical and observed transfer function phases show that stem motions lead water motions by  $\frac{1}{4}$  of a cycle at frequencies below about 0.1 Hz, but smoothly transition to being in phase at frequencies above about 0.8 Hz. Model-data agreement is good.]*

## IMPACT/APPLICATIONS

The fronts we measured are clear to remote sensors. Hydraulic control processes, which closely link frontal dynamics with bathymetry, may prove useful in the development of bathymetric inversion algorithms.

Buoyant plumes distribute river water and fine sediments. Observations of plume propagation and mixing provide an opportunity to improve understanding of mechanisms for transport of salt, heat, and fine sediment across tidal flats. Improved understanding of wind-generated currents would also likely improve understanding and prediction of such transport.

Understanding of wave dissipation by vegetation may improve understanding of fine sediment deposition, since many environments of rapid deposition include substantial saltmarshes.

A long-term goal is the development of accurate models for sediment transport across tidal flats. Testing the ability of sediment transport models to predict bathymetric evolution observed on tidal flats may contribute towards this goal.

## **RELATED PROJECTS**

Our project is a component in a wider Tidal Flats DRI. Our fixed data is available to other Tidal Flats researchers on the web. We have passed our ADCP data to Arete Associates, to help them test their remote estimates of surface velocity.

In support of Tidal Flats researchers Tim Milligan, Paul Hill, and Brent Law, we have also measured currents in Willapa Bay. We are now working with these researchers to compare turbulent dissipation rates estimated using our current meters with sediment flocculation estimated using their co-located instruments.

## **REFERENCES:**

Hogg, A.M., Ivey, G.N. and K.B. Winters (2001), Hydraulics and mixing in controlled exchange flows, *Journal of Geophysical Research*, 106, 959--972.

## **PUBLICATIONS:**

Mullarney, J., Henderson, Stephen M., (2010), Hydraulically-Controlled Front Trapping on a Tidal Flat, *Journal of Geophysical Research* [submitted, refereed].

Mullarney, J., Henderson, Stephen M., (2010), Wave-forced motion of submerged, single-stem vegetation, *Journal of Geophysical Research* [submitted, refereed].